Surprises in Higgs Searches at the LHC

LHC from Data to Discovery Workshop
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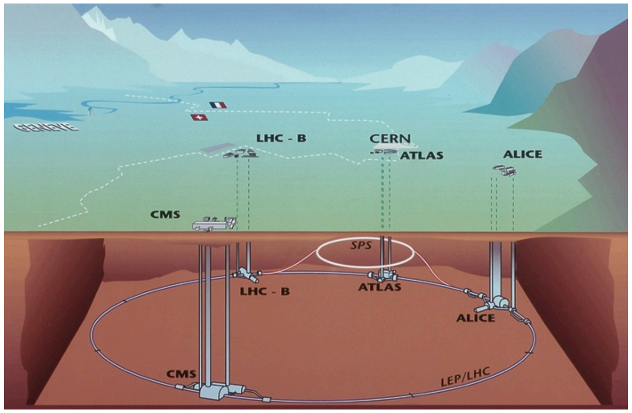
LHC: Dawn of a new era in particle physics

- Primary Goals of LHC
  – Probe dynamics of electroweak symmetry breaking (Higgs)
  – Find evidence of new physics (Dark Matter, SUSY, ED, etc.)

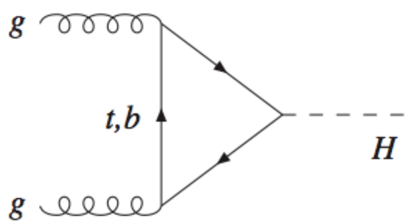
- Top factory: 1 top quark pair every second
  (10/day at Tevatron)

- Higgs factory?
  – 1 Higgs boson every minute in SM with $M_h = 200\ \mathrm{GeV}$
  – 1 “Observable” Higgs boson every 3 days in SM with $M_h = 200\ \mathrm{GeV}$

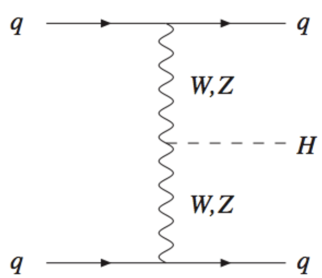


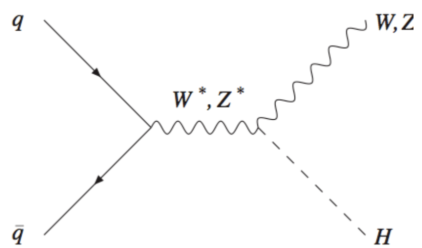
Higgs Factory?

Gluon fusion most dominant mode but many backgrounds present (many jets)

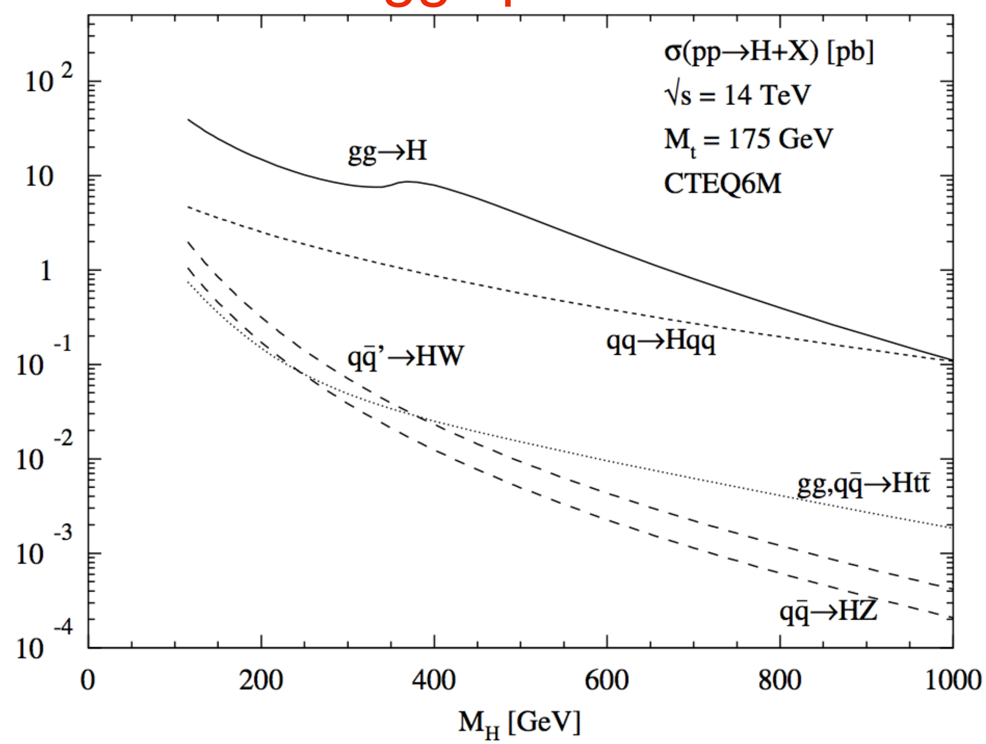


WBF and Z-Higgstrahlung weaker but may yield cleaner signals





SM Higgs production



The Higgs: Insight to Terascale physics

- Sampling of models:
  - Supersymmetry (MSSM, mSUGRA, SO(10) GUT, etc.)
    - Typically definite predictions of lightest Higgs mass
  - Extra dimensions (UED, RS, etc.)
    - Enhanced Higgs production
  - Composite models (Little Higgs, Technicolor, etc.)
  - Singlet models (xMSSM, xSM, etc.)
    - Reduction in production rate
  - Something else...

Must be prepared for both the contemplated changes in Higgs paradigm and the unexpected!

Statistical significance at the LHC

ATLAS TDR:

$$gg \to H_i \to ZZ \to ll\nu\nu$$

$$t\bar{t}H_i \to t\bar{t}b\bar{b}$$

$$WH_i \to 3W \to l\nu l\nu l\nu$$

CMS TDR:

$$WW \to H_i$$

$$H_i \to WW \to l\nu jj$$

$$H_i \to \tau\tau \to l + j$$

$$H_i \to \gamma\gamma$$

ATLAS & CMS:

$$gg \to H_i$$

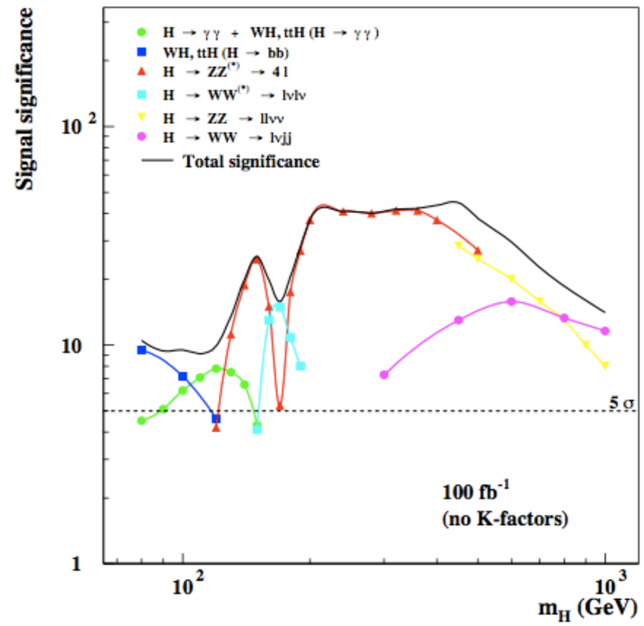
$$H_i \to \gamma\gamma$$

$$H_i \to ZZ \to 4l$$

$$H_i \to WW \to l\nu l\nu$$

Both ATLAS & CMS can do same searches

SM Higgs at ATLAS 100 fb^{-1}



The "golden channel", $H_i \to ZZ \to 4l$, dominates most of mass range (120 GeV < M_H < 600 GeV)

High significance when combined with $H_i \to \gamma\gamma$ for M_H < 120 GeV

Higgs discovery scaling

Scale statistical significances in ATLAS and CMS TDRs with altered production couplings and branching fraction to specific modes

$$\frac{S_X}{\sqrt{B}} \to \frac{S_X}{\sqrt{B}} \left(\frac{g_{hxy}}{g_{h_{SM}xy}} \right)^2 \frac{\mathrm{Bf}(h_i \to X)}{\mathrm{Bf}(h_{SM} \to X)}$$

Significance of individual modes summed in quadrature to obtain total significance

Surprise #1: Higgs could have reduced couplings

- Mixing between SM Higgs doublet and other scalars may reduce couplings with SM fields
  - Example: Neutral scalar singlet/doublet mixing

- Reduced couplings decrease production rate

- May take more integrated luminosity to discover Higgs boson

Singlet extended SM

Add real scalar singlet to SM Higgs potential

- Singlet interacts with SM only via Higgs

$$
\begin{aligned}
V &= \frac{m^2}{2} H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta_1}{2} H^\dagger H S + \frac{\delta_2}{2} H^\dagger H S^2 \\
&+ \left(\frac{\delta_1 m^2}{2\lambda}\right) S + \frac{\kappa_2}{2} S^2 + \frac{\kappa_3}{3} S^3 + \frac{\kappa_4}{4} S^4,
\end{aligned}
$$

Krasnikov
O'Connell, Ramsey-Musolf, Wise

$$
M_H^2 = \begin{pmatrix} \lambda v^2/2 & \delta_1 v/2 \\ \delta_1 v/2 & \lambda_S v^2/2 \end{pmatrix}
$$

Singlet mixing with SM Higgs can reduce couplings

Barger, Langacker, McCaskey, Ramsey-Musolf, GS

- Fields S and h mix
  - ➡ Mass eigenstates H_1 and H_2 decay to SM fields via mixing

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} h \\ S \end{pmatrix}$$

Branching fractions:

$$\mathrm{BF}(H_1 \to X_{SM}) = \mathrm{BF}(h_{SM} \to X_{SM})$$

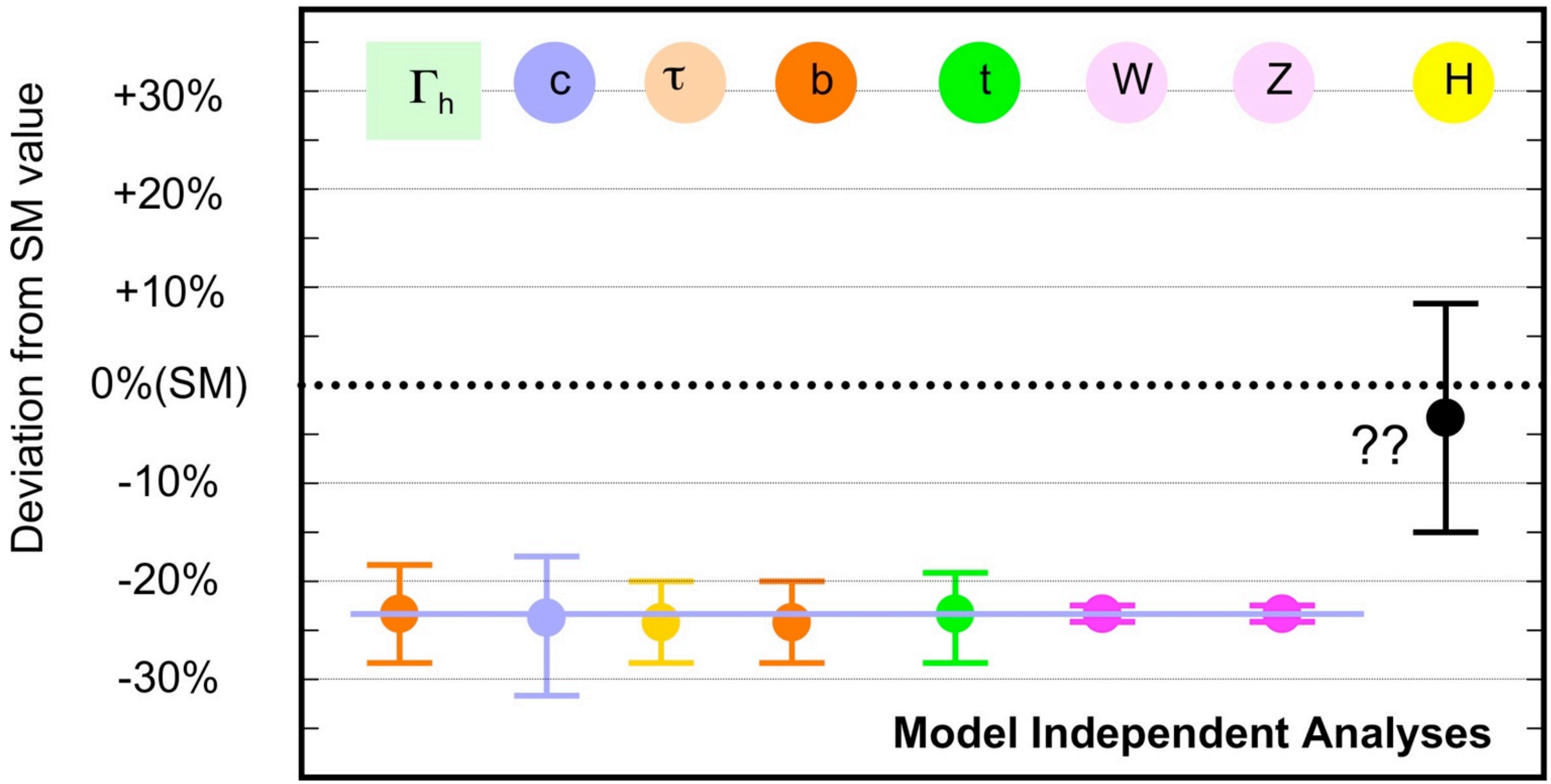
$$\mathrm{BF}(H_2 \to X_{SM}) = \frac{\mathrm{BF}(h_{SM}\to X_{SM})}{1+\Gamma(H_2\to H_1 H_1)/\Gamma(H_2\to X_{SM})}$$

Signal reduction factor:

$$\xi_i^2 = g_{H_i}^2 \frac{\mathrm{BF}(H_i \to X_{SM})}{\mathrm{BF}(h_{SM} \to X_{SM})}$$

Singlet-Higgs mixing

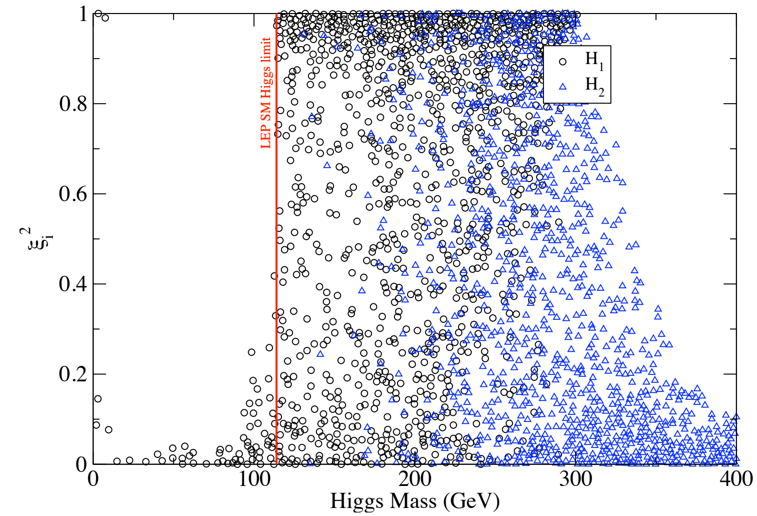
- Higgs couplings reduced **universally** by mixing parameter



Yamashita

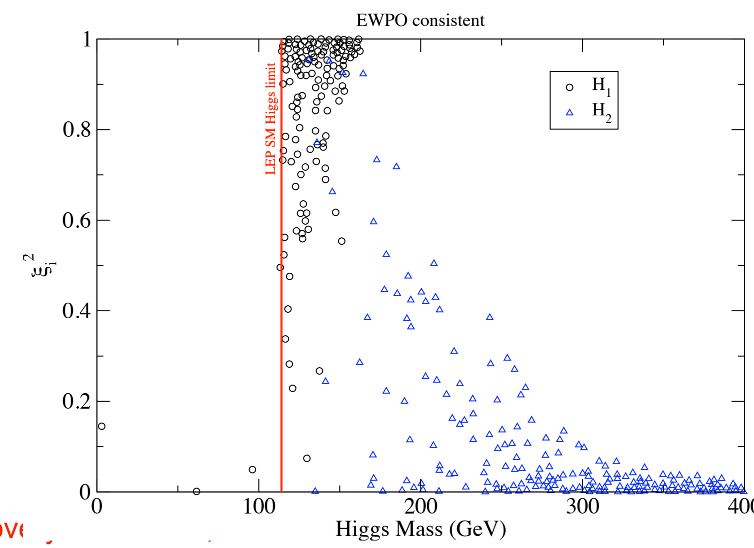
Surprise #2: Higgs could be lighter than LEP2 bound

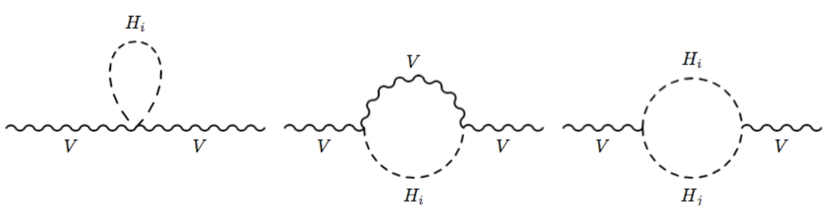
- Due to reduced couplings, the LEP2 exclusion region can be partially allowed



- Higgs mass may be well below LEP limit

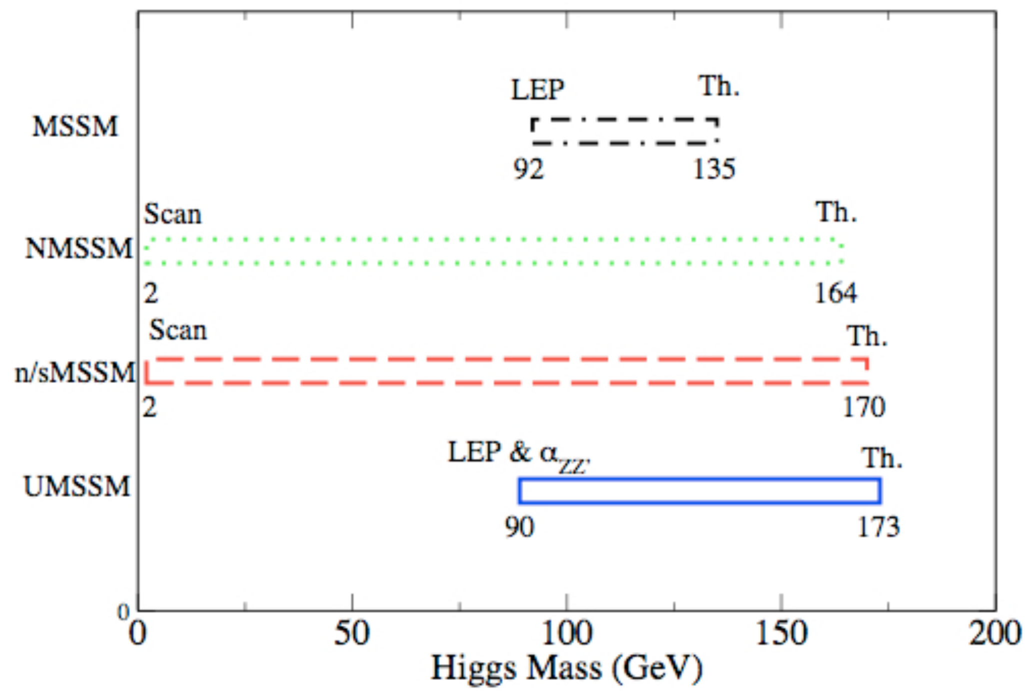
- Electroweak precision constraints pushes SM-like state lighter (singlet can be quite heavy)





Lightest CP-even Higgs mass range in xMSSM models

Singlet extended MSSM: Very light H_1 possible in NMSSM (cubic) and nMSSM (tadpole) models

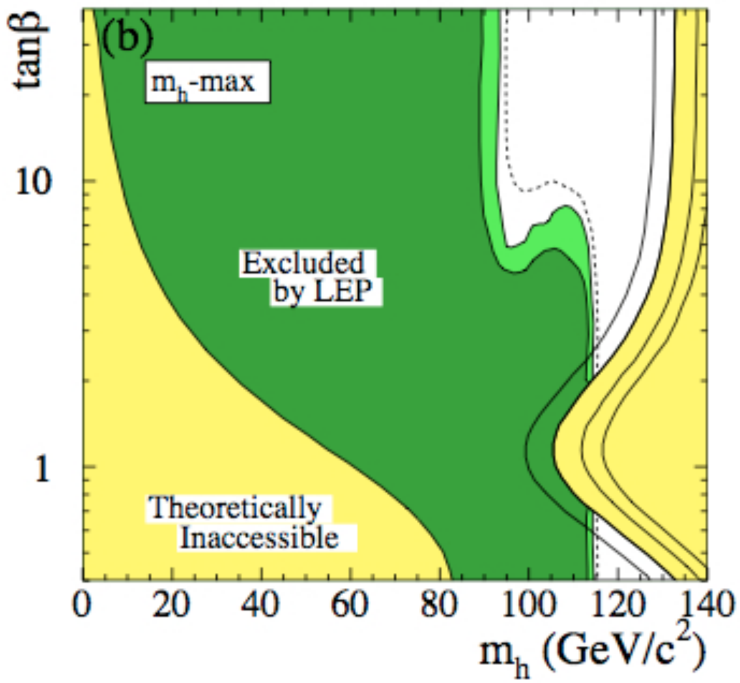


Singlet interactions can also increase the lightest Higgs mass above MSSM expectation:

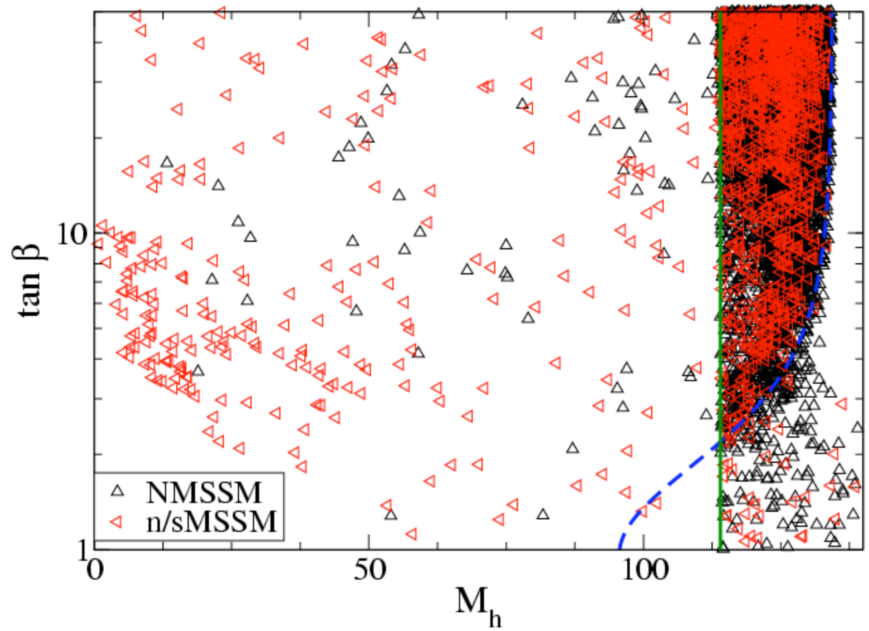
$$
\begin{aligned}
M^2_{H^0_1} \leq\ & M_Z^2 \cot^2 2\beta + \widetilde{\mathcal{M}}^{(1)}_{rad} && \text{MSSM} \\
& + \frac{1}{2} h_s^2 v^2 \sin^2 2\beta && \text{NMSSM, n/sMSSM} \\
& + g_{Z'}^2 v^2 \left(Q^2_{H_d} \cos^2 \beta + Q^2_{H_u} \sin^2 \beta \right)^2 && \text{UMSSM}
\end{aligned}
$$

Easing the LEP tension

BEFORE
(MSSM)



AFTER
(Cubic & tadpole Models)



Variety of models allow light Higgs Bosons

Surprise #3: Higgs could have enhanced couplings

- Fermion couplings can be enhanced in Multi-HDM where VEV is shared
  - e.g. $g_{hb\bar{b}}, g_{h\tau^+\tau^-}$ In 2HDM-II when $\tan\beta$ is large
    Field content: $\Phi_u, \quad \Phi_d$
  - Lepton couplings only can be enhanced in lepton-specific 2HDM
    Field content: $\Phi_q, \quad \Phi_\ell$

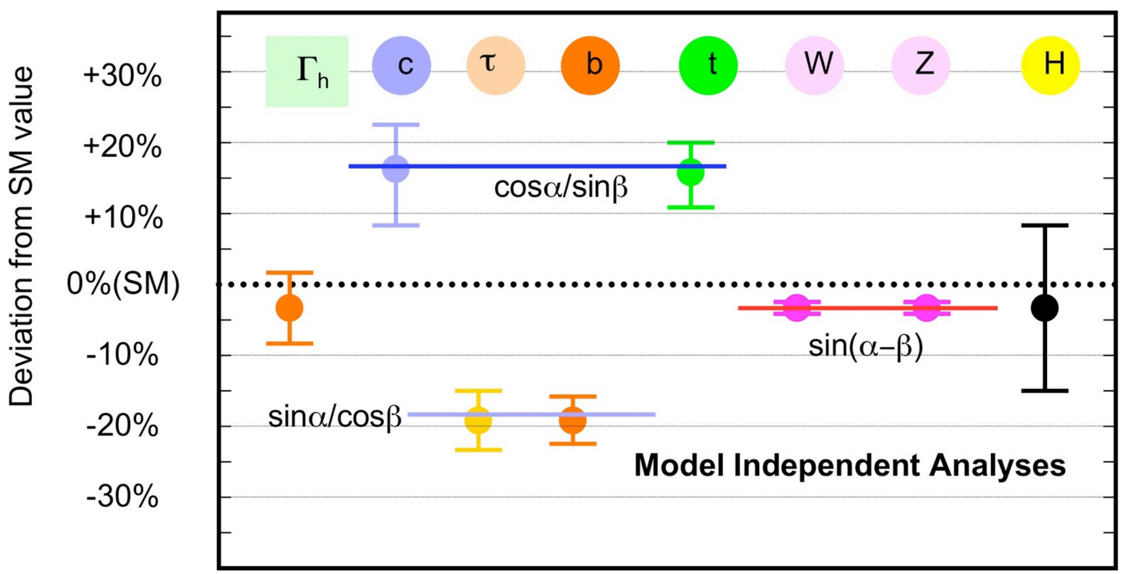
- Loop induced couplings in gg fusion, $h \to \gamma\gamma$
  - Fermion coupling enhancement
  - Interference
  - Additional contributions from new field content (UED, SUSY, vector-like quarks)

Multi-HDM

- VEV sharing can increase Higgs coupling to fermions
- Coupling patterns can point to underlying Higgs structure
  - 2HDM-I, 2HDM-II, 3HDM-L, Flipped 2HDM-II, Lepton specific 2HDM
  - Additional sterile doublets? (contribute to W mass, but do not couple to fermions)
  - Additional singlets?

Barger, Logan, GS in preparation

2HDM-II (SUSY)

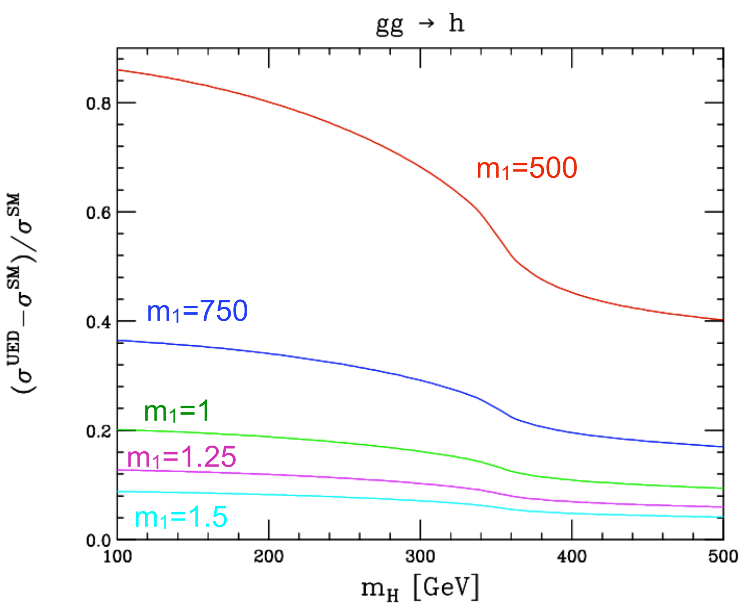


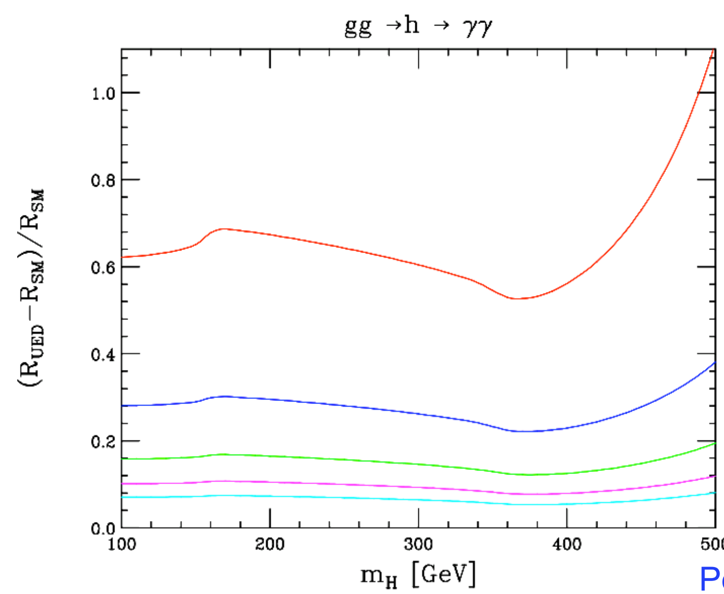
Yamashita

Enhanced Higgs production

- New physics can enter gluon fusion loops
- KK contributions or 4th gen. Fermion doublet can increase rate substantially!
- Dominant effect from top quark KK tower
- M_1 - compactification mass

~650 GeV preferred by Dark matter relic abundance



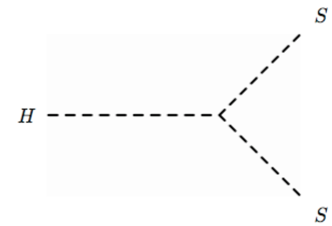


Petriello

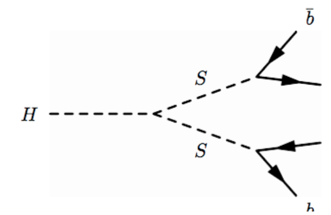
Window to new physics!

Surprise #4: Higgs may decay through exotic channels

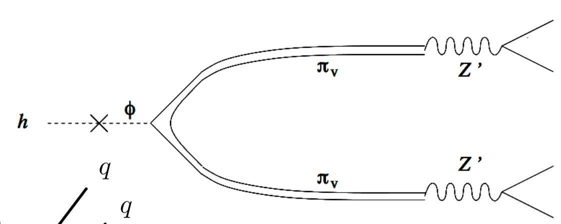
- Higgs may decay:
  - To invisible states (neutrinos, DM, etc.)



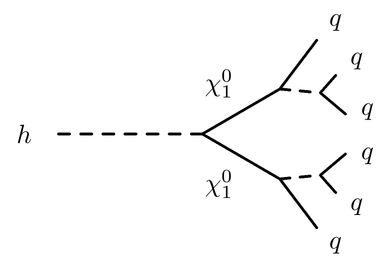
  - Through light CP-even and/or CP-odd states to b, τ pairs



  - Through v-hadrons in Hidden Valley models
    - Displaced Higgs decays possible (Strassler and Zurek)



  - To multijets in R-parity violating SUSY



- Rate of traditional channels reduced

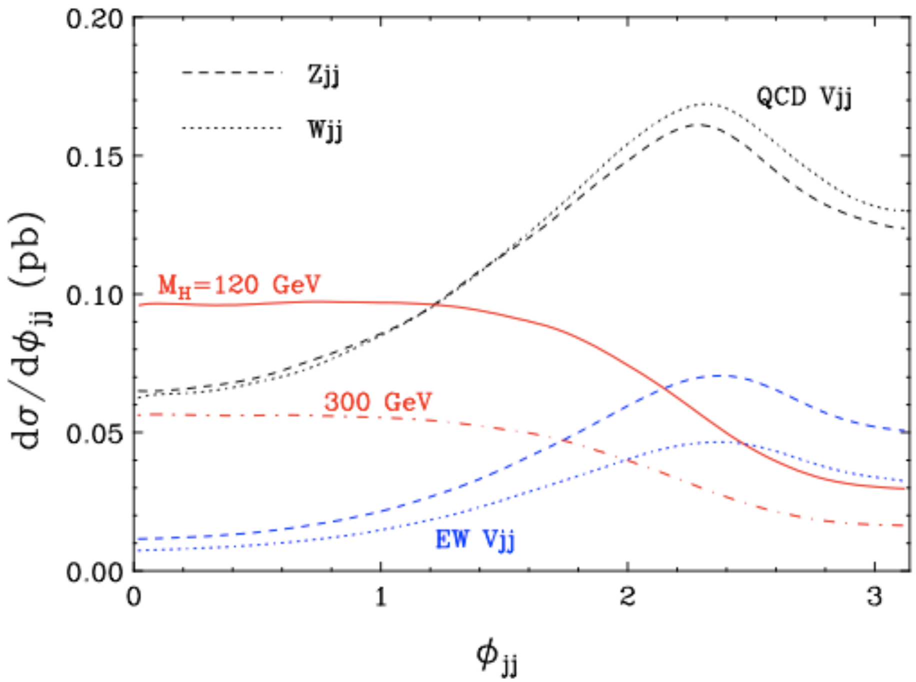
- Have to rely on new search techniques if new modes dominate

Finding an invisibly decaying Higgs

Weak boson fusion:

Extract signal with cuts on azimuthal correlation of forward jets and large missing p_T

Eboli and Zeppenfeld



Z-Higgstrahlung:

Cuts on dilepton separation and invariant mass to extract signal

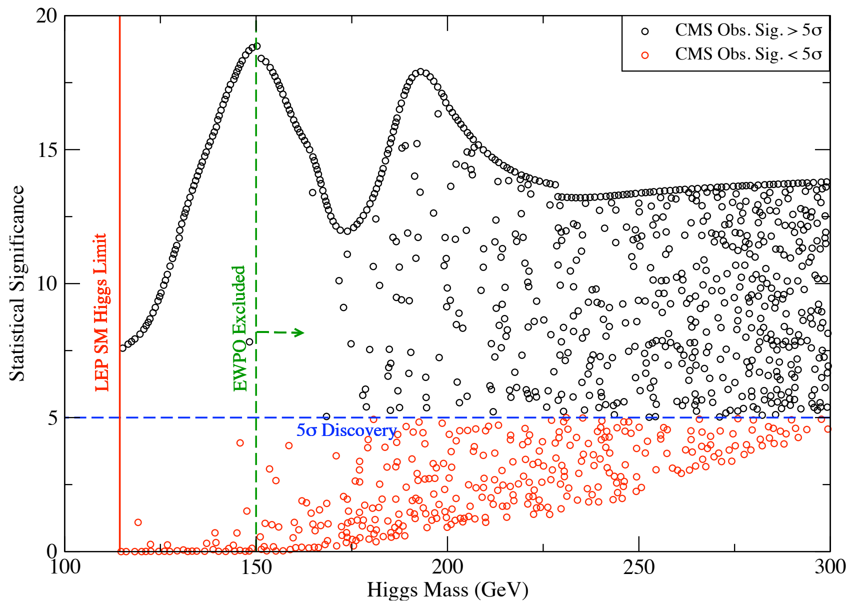
Davoudiasl, Han, Logan

Combined → model independent mass determination

Examples of Invisible Higgs decay

- Possible in:
  - (x)MSSM with light neutralino
  - Singlet extended SM with Z_2 symmetry (Barger, McCaskey, Langacker, Ramsey-Musolf, GS)
  - Higgs has connection to neutrino sector (Graesser)

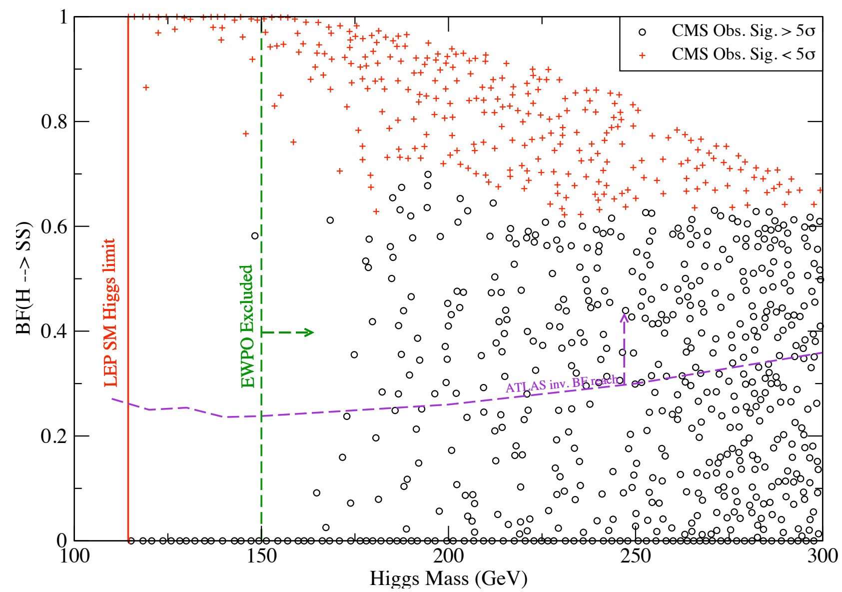
CMS 30 fb^{-1}



Red: not disc. with visible modes

Black: disc. with visible modes

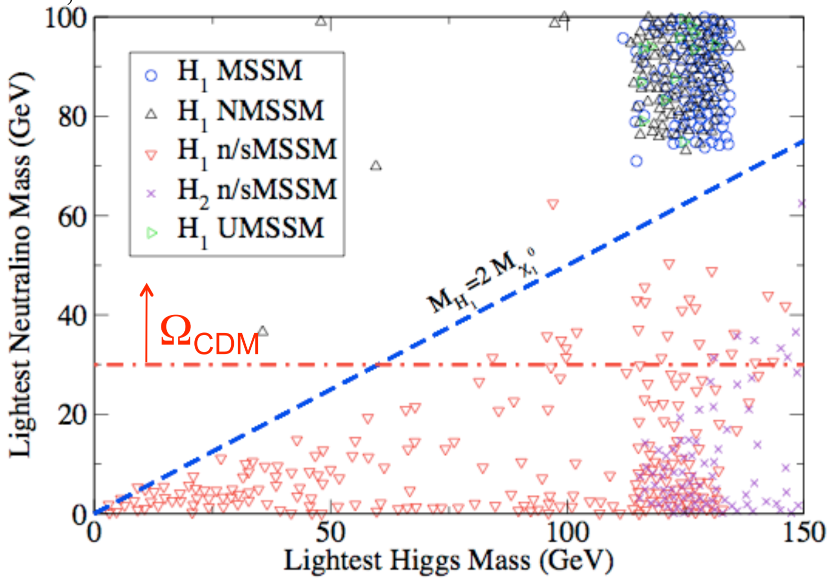
ATLAS, CMS @ 30 fb^{-1}

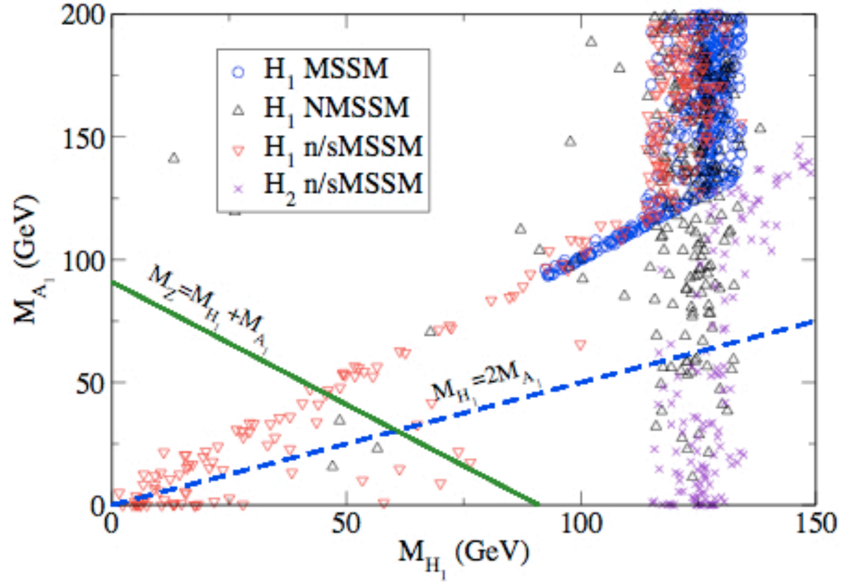


Higgs boson still discoverable even if invisible decays allowed!

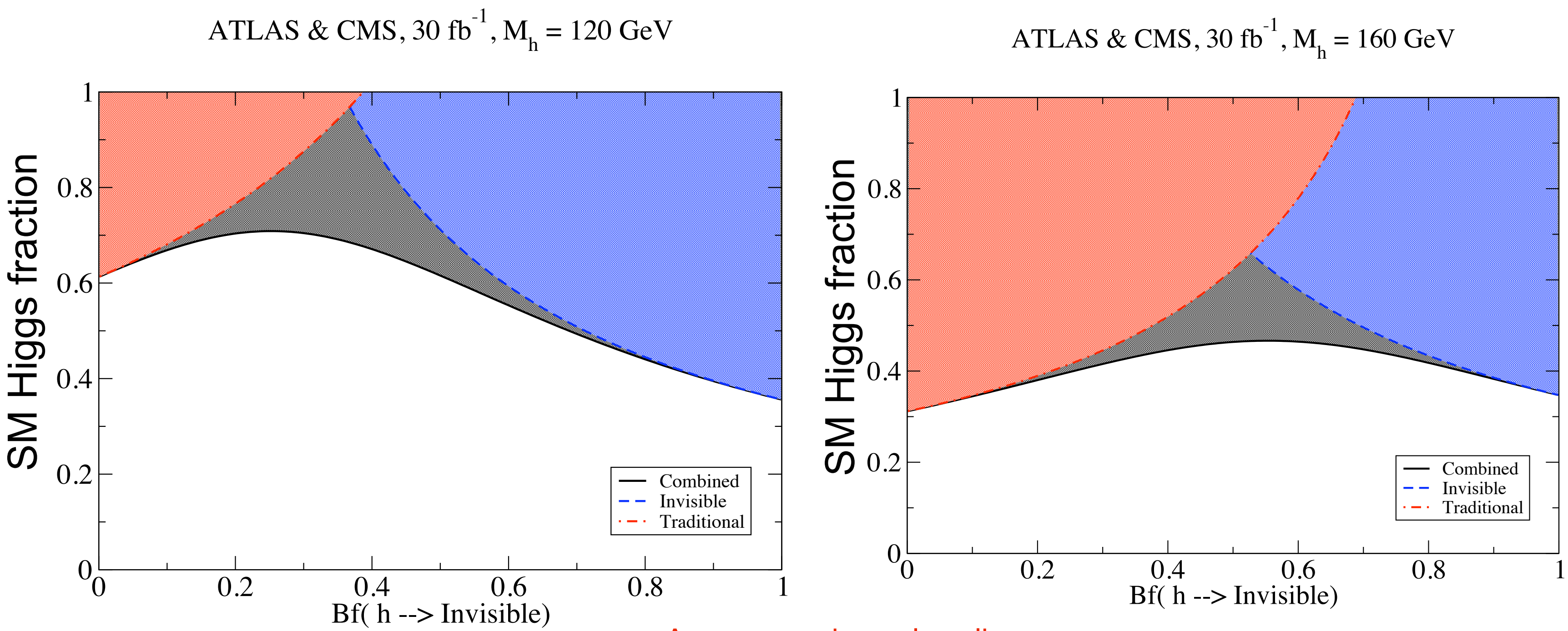
Example: xMSSM with light neutralinos and/or CP-odd Higgs

$H_{1,2} \to \chi_1^0 \chi_1^0$ (invisible decays) $H_{1,2} \to A_1 A_1$ (extended decays)





- Most of mixing-invisible decay space can be covered at LHC with modest luminosity
- Difficult if more mixing-singlets are included



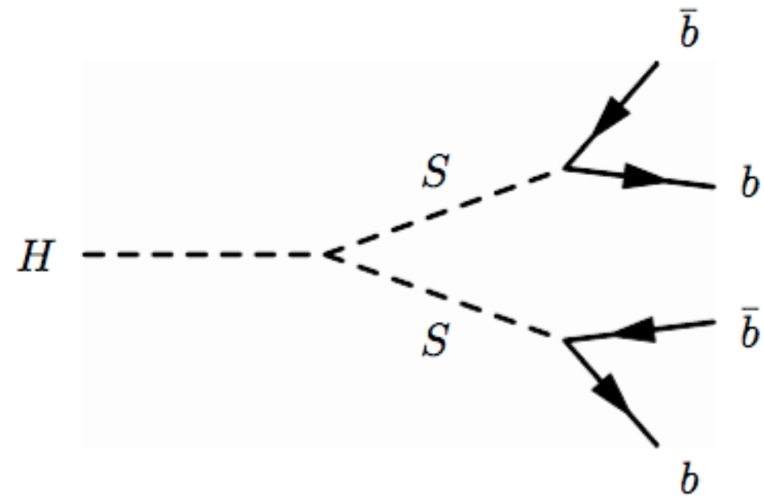
Assumes universal scaling

Barger, Langacker, McCaskey, Ramsey-Musolf, GS

New Higgs decay modes

Extended decays through new scalar:

$$W\,H \to l\nu + 4b$$
$$W\,H \to l\nu + 2b + 2\tau,$$



Natural in singlet models
– xSM, NMSSM, nMSSM etc.

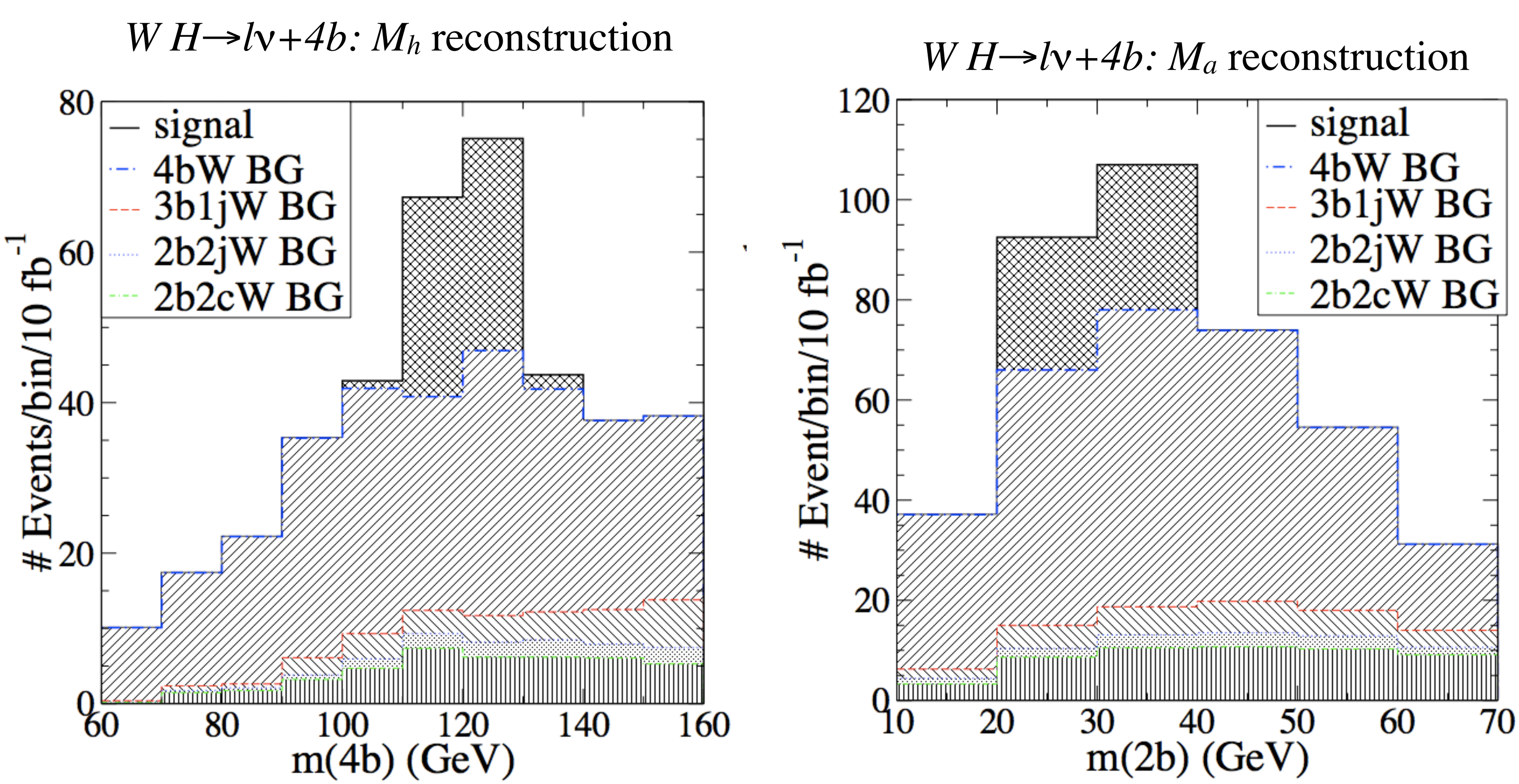
Extensive literature for $h \to aa$ searches in Singlet + MSSM

Carena, Han, Huang, Wagner
Cheung, Song, Yan
Gunion, Dermisek, McElrath
Chang, Fox, Weiner
Graham, Pierce, Wacker

Model Independent Search

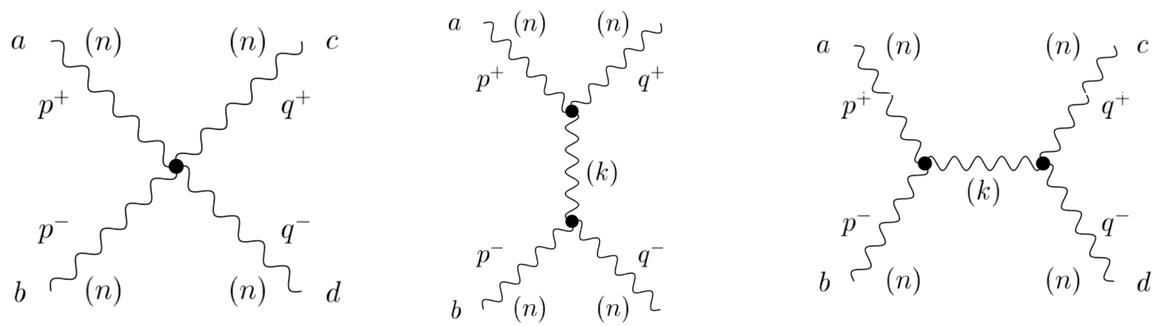
- Associated WH channel where W→lν (background rejection)
- Relative Higgs production and branching to 4b: $C^2_{4b} = 0.5$

Carena, Han, Huang, Wagner



Surprise #5: No Higgs at all!

- Unitarity violation in $W_L W_L$ scattering without Higgs boson
- Solved with new fields that unitarize longitudinal gauge boson scattering
- For example, $W_L W_L$ scattering can be unitarized by exchange of infinite tower of KK modes from a warped extra dimension



- May instead search for resonances of unitarizing modes

Surprise #6: The unexpected

?

Conclusion

- Discovering the Higgs and its connection to massive gauge bosons will complete the picture of the Electroweak symmetry breaking

- Important to keep in mind that there may be twists to the standard picture
  - Enhanced/Reduced production rates, branching fractions
  - Higgs boson can still be lighter than LEP bound (if sufficiently mixed)
  - Exotic decay modes

Many surprises in the Higgs sector
may be in store for us at the LHC!